Aurora Robotics X-Hab Technical Final Report

Modular Robotic Construction

NASA Moon to Mars X-Hab 2024-2025

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Project Team: Andrew Mattson (CS BS/MS), Elliot Madsen (ME BS), Delano Horner (ME BS), Daniel Schliesing (ME BS), Kory Lamme (ME BS)

Proposing Faculty (PI): Dr. Orion Lawlor <lawlor@alaska.edu>, +1 907 474-7678
Associate Professor of Computer Science
Construction Expert: Dr. Nima Farzadnia
Assistant Professor of Civil Engineering

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1. Abstract

The Aurora Robotics Lab at the University of Alaska Fairbanks participated in the 2024–2025 NASA X-Hab Academic Innovation Challenge to explore modular robotic construction for lunar surface infrastructure. Our project focused on designing and partially demonstrating a teleoperable and automatable robotic system capable of assembling a micrometeoroid-resistant arch structure from modular steel truss segments. Our Excahauler robot, developed for the NASA Break the Ice Lunar Challenge, was equipped with a modular manipulator and end-effector designed for aligning and connecting trapezoidal trusses. Given time constraints, we used a 3D-printed scale model to validate structural behavior and backfill performance using regolith simulant. Time and resource constraints prevented completion of a full-scale robotic assembly, but our team demonstrated essential capabilities including robotic lifting, modular interface design, and structural load testing. The project also resulted in lessons in systems engineering, scope management, and interdisciplinary collaboration, contributing both technical insight and educational value to future lunar construction efforts.

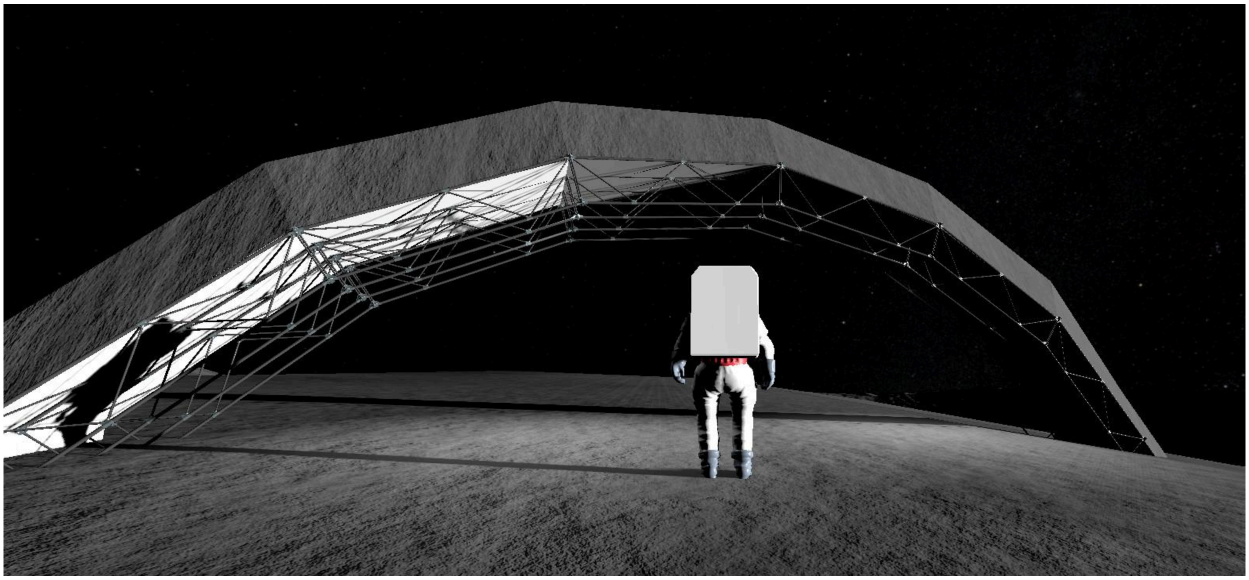
2. Introduction

For the 2024–2025 X-Hab Academic Innovation Challenge, we at the Aurora Robotics Lab investigated modular robotic construction techniques for lunar surface infrastructure. Our focus was on the design, partial fabrication, and ground demonstration of a steel truss-based arch structure that could, in extraterrestrial contexts, provide protection against micrometeoroids, dust, radiation, and potentially thermal insulation, resulting from layers of backfilled regolith on the structure.

2.1 Project Background and Relevance

NASA's Artemis program aims to establish a sustainable human presence on the Moon, requiring reliable, scalable surface infrastructure. Among the challenges are the harsh lunar environment, limited crew time, and the need for autonomous or teleoperated robotic systems capable of performing complex construction tasks. Our project addresses these challenges by exploring a modular construction approach using a single modular robotic platform and reusable structural components.

We aimed to demonstrate the feasibility of robotic assembly of such structures on Earth, with extensibility to lunar and Martian missions. This work aligns with NASA's strategic goals for surface infrastructure and ISRU (in-situ resource utilization), while also advancing student experience in systems engineering and hands-on prototyping.



Concept of a completed lunar arch structure with regolith backfill made in our Godot-based lunar simulator. We ended up selecting a slightly different design.

2.2 Team Composition and Structure

The team consisted of undergraduate and graduate students from mechanical engineering, computer science, and computer engineering. Each member contributed to important aspects of the design process, from CAD modeling and simulation to robotic control and fabrication. Roles evolved over the semester as project demands changed, with leadership and planning responsibilities becoming more centralized over time.

Name	**Discipline**	**Role**
Andrew Mattson	Computer Science BS/MS	Team Captain, Software Lead
Elliott Madsen	Mechanical Engineering BS	Hardware Lead
Delano Horner	Mechanical Engineering BS	Logistics and Testing Lead
Kory Lamme	Mechanical Engineering BS	Thermal Lead
Daniel Schliesing	Mechanical Engineering BS	Visualization Lead
Dr. Orion Lawlor	Computer Science PhD	Faculty Advisor

The project was completed as part of two academic courses at UAF: CS 493 (Fall 2024) and CS 454 (Spring 2025), both focused on systems engineering and interdisciplinary design.

2.3 Project Timeline and Milestones

Our work followed the standard X-Hab design review process:

- **System Definition Review (SDR)** – October 4th, 2024
- **Preliminary Design Review (PDR)** – November 15th, 2024
- **Critical Design Review (CDR)** – January 24th, 2025
- **Progress Checkpoint Review (PCR)** – April 18th, 2025
- **Final Demonstration & Report** – May 23rd, 2025

These milestones guided the technical progression of our design, helping structure the team's tasks into clearly defined phases: concept development, simulation and prototyping, hardware design, fabrication, and testing. We received valuable feedback from our NASA subject matter experts and other experts during these reviews, and during our meetings about every 2 weeks.

2.4 Initial Goals and Scope

Our original goals included:

- Designing a modular steel truss structure that could be robotically assembled on the lunar surface.
- Equipping a robot with a manipulator and tool interface capable of aligning, lifting, and connecting trusses.
- Demonstrating full-scale robotic assembly and regolith simulant backfill in an analog test site.

We did not demonstrate a full-scale assembly due to scope and resource constraints, many core milestones were met. Our deliverables from the project included:

- We designed several iterations of a modular steel truss, the trapezoidal L-truss, that can be assembled via self aligning push connection to produce a variety of flat or curved structures.
- We built a robot end effector that could grab and manipulate our trusses.
- We built a novel robot arm 2500:1 reduction ratio gearbox, which we used for robotic demonstrations.
- We demonstrated that our robot could assemble our truss elements via teleoperation.

Our results are described in detail in the following sections.

3. Concept of Operations

This section outlines the intended operational use of the system in a lunar environment, followed by the approach taken for terrestrial demonstration. The concept of operations (ConOps) covers deployment, assembly sequencing, robotic behavior, and environmental considerations.

3.1 Lunar ConOps (Long-Term)

In the envisioned lunar deployment scenario, modular steel truss segments and robotic systems are delivered via a logistics lander to the Artemis Base Camp. The truss structure topped with regolith serves primarily as a micrometeoroid and radiation barrier, with potential also for thermal protection. The long-term concept supports a scalable, repeatable, and modular construction process for building shelters, equipment bays, or shielding enclosures.

The arch structure construction process is divided into five sequential phases:

Phase 1: Site Preparation

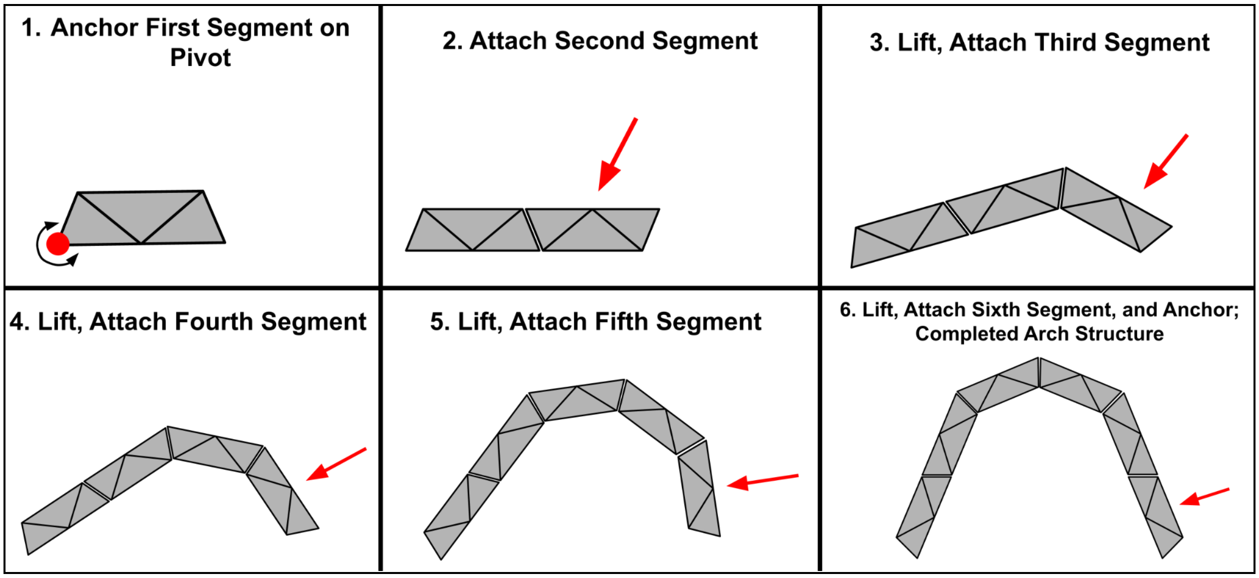
- The Excahauler (or future derivative) robot performs terrain leveling using excavation tool attachments (jackhammer, grinder drum, bucket).
- Trenches may be dug with a trenching tool to provide partial submersion and anchoring for the initial arch segments.

Phase 2: Material Unloading

- Truss segments are unloaded from the lander using a forklift tool.
- Segments are staged near the construction site in the order needed for assembly.

Phase 3: Structural Assembly

- Using its modular manipulator and clamping end-effector, the robot lifts and aligns each truss segment in the first row.
- Segments are joined using the designed connectors at each end.
- Once attached together, the entire row is lifted by one robot (as seen in the single-row cross section images below) to allow another identical robot to begin connecting the next row of truss segments.



Phase 4: Regolith Backfill

- Regolith is applied to the structure using some combination of a snowblower-like ballistic thrower, cable-driven bucket, or manual shoveling tools attached to the robot.

Phase 5: Post-Construction Use

- Once constructed, the arch structure can serve as a radiation and micrometeoroid shelter for equipment or crew, as thermal shielding for sensitive systems, or as a base layer for additional surface infrastructure.
- The structure is designed to be modular and potentially reconfigurable.

3.2 Ground Demonstration ConOps

Due to budget, time, and environmental constraints, our 2024–2025 demonstration focused on scaled robotic interaction and physical prototyping of key system components. The goal was to validate modularity, connection mechanisms, and robotic handling under realistic conditions.

Phase 1: Design and Simulation

- Truss geometry and connection strategies were refined using CAD and finite element simulations.
- The Godot-based simulator was used to visualize system-level assembly constraints and assess robotic reach, clearance, and layout.

Phase 2: Fabrication and Scale Testing

- A small number of full-scale truss segments were fabricated using a plasma cutter and manual assembly.
- A 3D-printed 1:10 scale model of the arch structure was produced for physical testing.

- Basalt dust served as a lunar regolith simulant for backfill and loading tests.

Phase 3: Robotic Assembly Testing

- The Excahauler robot was outfitted with a custom modular end-effector designed for lifting and aligning truss segments.
- Teleoperated robotic testing demonstrated lifting, transporting, and connecting truss segments.
- Completed robotic segment-to-segment connection in the lab environment.

Excahauler lifting a truss segment in the lab.

Phase 4: Load and Backfill Validation

- The scale model arch was successfully backfilled and top-loaded to simulate lunar loading conditions.
- These tests confirmed the structure's ability to support loads far exceeding expected regolith mass in 1/6 g.
- More information in Section 5: Testing and Validation.

4. System Design

4.1 Structure

Structures are used on planetary surfaces to protect against the local hazards:

- Earth structures protect against rain, wind, and air temperature changes.
- Lunar structures protect against micrometeorites, solar and GCR radiation, and ambient radiative heating changes.
- Mars structures protect against GCR radiation, and temperature changes.

Our lunar-focused design emphasizes micrometeoroid protection with additional thermal shielding. Recent work on lunar seismic analysis (Lee et al, 2025) indicates that 50-year moonquake incidence may exceed lunar gravitational loads.

Structural elements need to cover a wide variety of applications:

- **Towers** for reaching solar energy at poles
- **Flat** roofs for landing areas, dust protection
- **Barrel** roofs (arches) for garages
- **Domes** for habitats, or better protected garages
- **Ring** blast walls around landing pads
- Retaining **walls** buried into regolith

Foundation prep and structure outfitting are also important aspects of construction.

The trade space for extraterrestrial construction approaches is extremely large, and many groups have explored options for assembling structures on planetary surfaces:

Approach *Authors*	*Summary*	*Advantages*	*Limitations*
ARMADAS Voxels NASA Ames (Gregg et al, 2024)	Robots crawl through a voxel grid that they can emplace. Variety of voxel types allows 'programmable matter'.	Very general purpose, while being amenable to fully automated emplacement.	Voxels have low aspect ratio, so may not be very structurally efficient for anisotropic loads like spans.
Polaris: Tall Lunar Tower (TLT) NASA Langley, HQ TLT slideshow	Robotic base assembles a tower bay by bay from flat sticks.	Ground demonstrated full tower assembly.	Can only build one tower, on top of itself.
Precision Assembled Space Structures (PASS) NASA Langley (Doggett et al, 2022)	Screw assembly of rigid TriTruss segments.	Ground demonstrated large stiff accurate structures, suitable for telescope.	Not clear how to pack TriTrusses and retain good properties. Not clear TriTrusses are the right shape for surface structures.
Lunar Safe Haven NASA Langley & Marshall (Wong et al, 2022)	Uses LSMS crane robot to emplace regolith onto a structural frame.	Clear phases from initial groundwork to extensive interconnected shelters.	Does not appear to have many ground demonstrated features. (In particular, manipulating or joining structure elements.)

Approach *Authors*	*Summary*	*Advantages*	*Limitations*
MMPACT NASA Marshall ICON corporation	Regolith-based materials for ISRU construction. (Moon-to-Mars Planetary Autonomous Construction Technology)	Minimal landed mass due to ISRU feedstock.	Currently only small-scale demonstration elements.
GITAI robotic construction GITAI corporation (GITAI on YouTube)	Uses inchworm robot arm (TRL 6) to pick up and manipulate small structural elements.	They have demonstrated extensive element joining, welding, and detailed outfitting tasks.	Only proven with small structural elements.
Origami Packaging Many groups	Uses folding to compact structural elements into a small space.	Structure can fold flat for easy shipping, then unfold easily.	Difficult to make a stiff structure, many buckling modes possible.
Trapezoidal Truss Segments This Project	Uses push-connect segments that can assemble in curved or straight lines.	Can build strong towers, arches, or bridges.	Default segment topology assembles in 2D, so fully 3D structures like domes require additional joining plates.

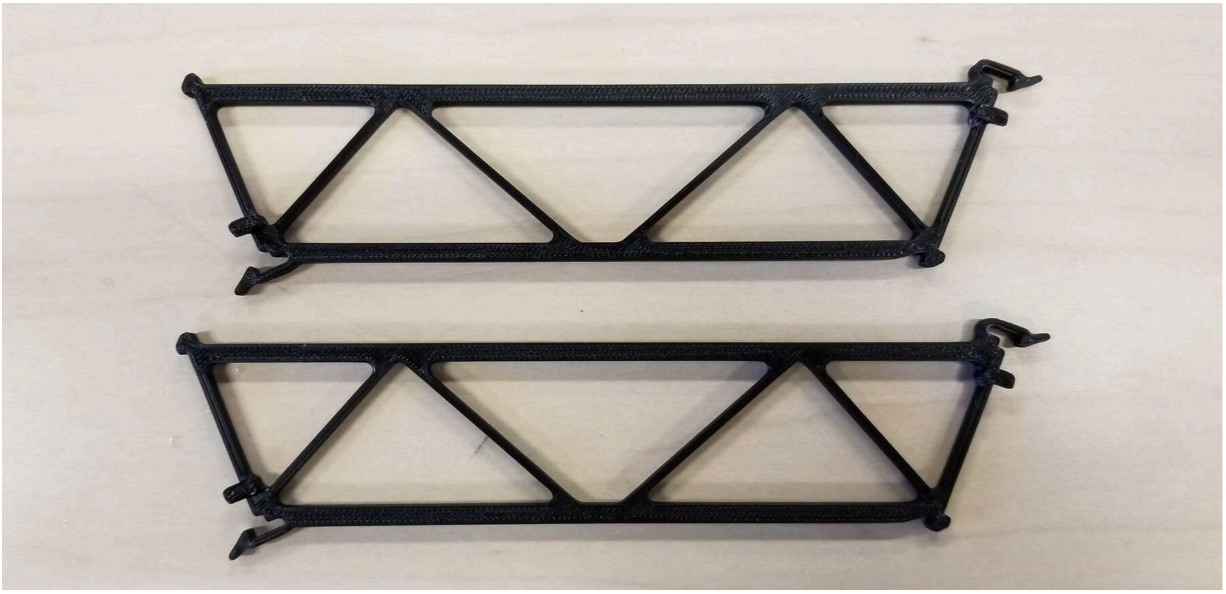
See Appendix A.1 for a summary diagram of the construction trade space, and Appendix A.2 for some of the alternate construction approaches we evaluated.

By our critical design review (CDR) we chose L-truss, a trapezoidal truss that can be assembled into straight or curved structures, designed as a strong lightweight truss using a small number of modules for a large structure. L-truss modules assemble endplate to endplate, ideally with push-connect latches that would not require any fasteners or active robot parts for assembly.

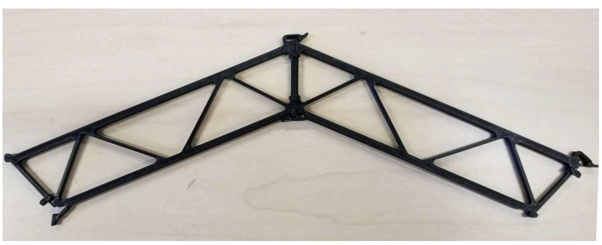
The basic L-truss shape is a trapezoid, so they curve when assembled with translational symmetry, but rotating one trapezoid cancels out the curvature and produces a straight structure, as shown in the figures on the next page.

A 3D printable model of our L-truss in 1/10 scale with a print-in-place flexure latch is available:

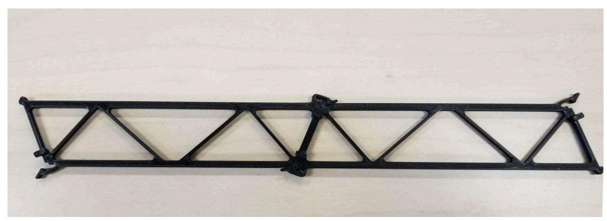
https://www.printables.com/model/1305834-trapezoidal-l-truss-clip-together-construction-mod



Two flat L-truss construction modules, 3D printed version with push-connect flexure end latches.



Joining modules end to end gives a curved segment, for arches, domes, or curved walls.



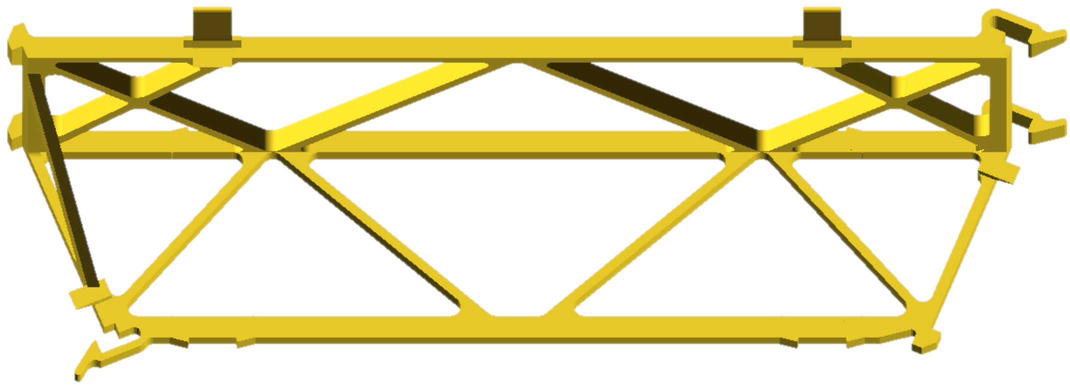
Rotating one module 180 degrees results in a straight segment, for flat roofs, floors, or walls; or towers.

Flat L-truss modules have two main drawbacks:

1. The thin section suffers buckling instability outside of its plane.
2. There is no obvious location to add a cover to support regolith backfill.

We can resolve both drawbacks by adding an upright rectangle over the long top truss member. This provides a third point of contact between adjacent modules, making them more stable against buckling. It also provides a surface that could be covered with a mesh or fabric to support backfill, and this covering could be added before, during, or after standing up the structure.

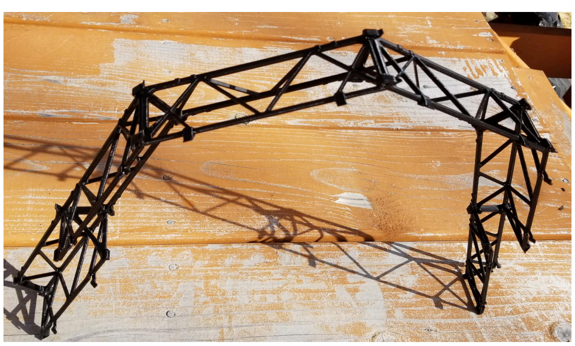
The upright does increase the packing complexity for stowed modules, but they partially nest and with carefully designed end latches could reach relatively high shipping density. Truss assembly or ISRU fabrication could result in even higher density.



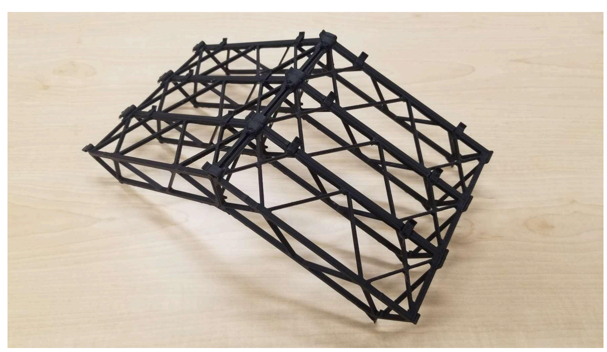
Full L-truss module with upright rectangle.

Six full L-truss modules stacked in a shipping configuration.

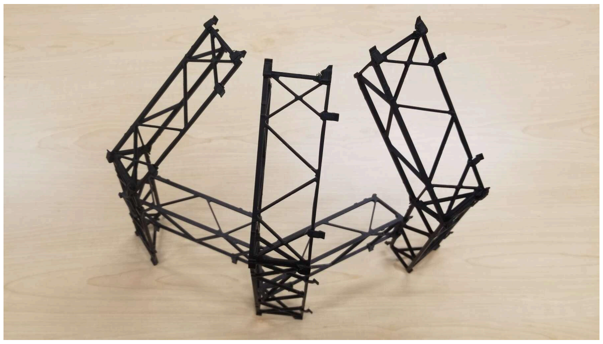
These modules can be assembled into a wide variety of configurations for horizontal and vertical construction tasks.



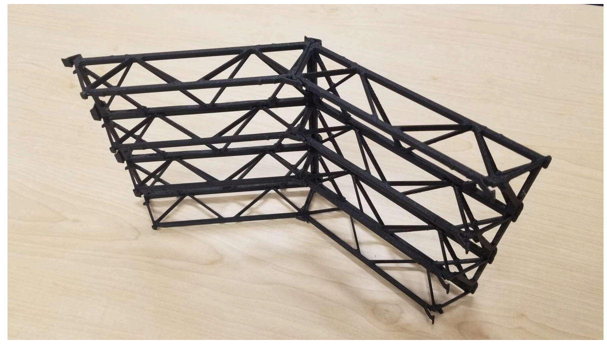
A 1-section 6-segment arch.



A 3-section 2-segment arch or bridge.



An approximate dome shape, assembled from a set of trusses. Full geodesic domes would require specialized vertex plates to join the truss segments.



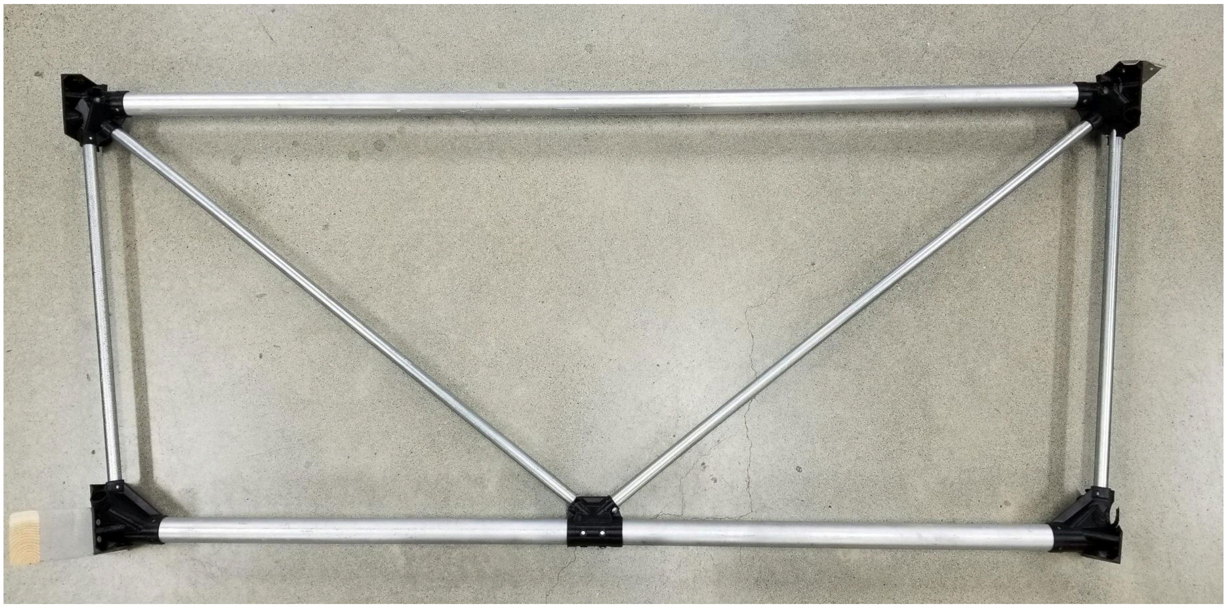
Stacked trusses to make a retaining wall shape. The regolith contact surface would be away from the viewer here, and could use the same uprights (with a suitable covering).

A 1-section 3-segment arch, with flat L-truss plates used as the crucial foundation element, in fluffy basalt rock crusher dust (NP-1, similar to BP-1 regolith simulant).

The same arch supporting 12kg (118N).

We have built four iterations of full-scale truss designs:

1. (Fall 2024) 3D printed **plastic joint** truss. This was useful for geometry prototyping, but testing showed it wasn't strong enough for a large scale assembly demonstration.
2. (Winter 2024-25) **Welded tube** truss. This was our primary CAD target through the CDR, but it was very difficult to cut accurate fishmouth profiles on the round tubes, which were also difficult to weld without distortion.
3. (Spring 2025) **Plasma-cut endplate** truss. This was designed to be much more manufacturable while being repeatable with push-connect, but is still relatively immature.
4. (Summer 2025) **Hybrid** truss with box tubing with printed end funnels. This combines the strength of metal with the manufacturability and easy assembly of printing.

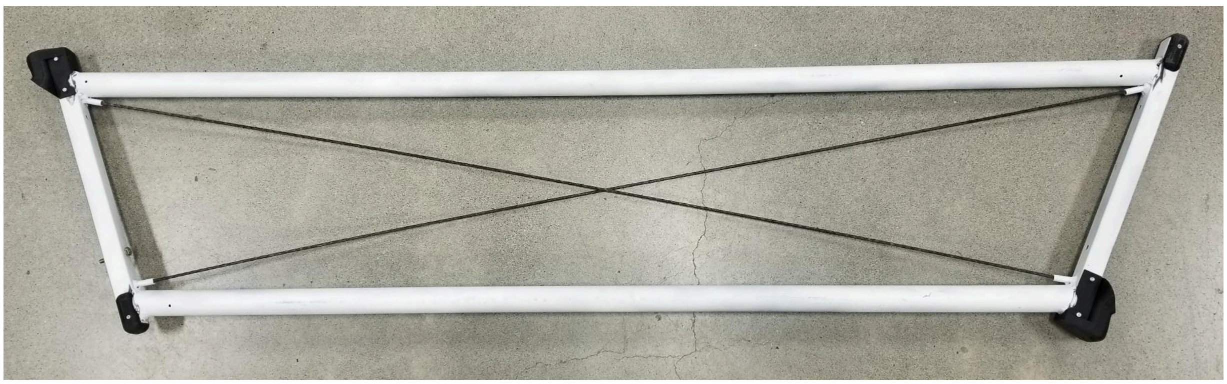


Early truss design with **plastic joints**, which was useful for understanding the geometry.

Our CDR design used **welded tubes**, which was strong but difficult to manufacture.

Plasma-cut endplates simplified manufacturing, but were still difficult to robotically push connect.

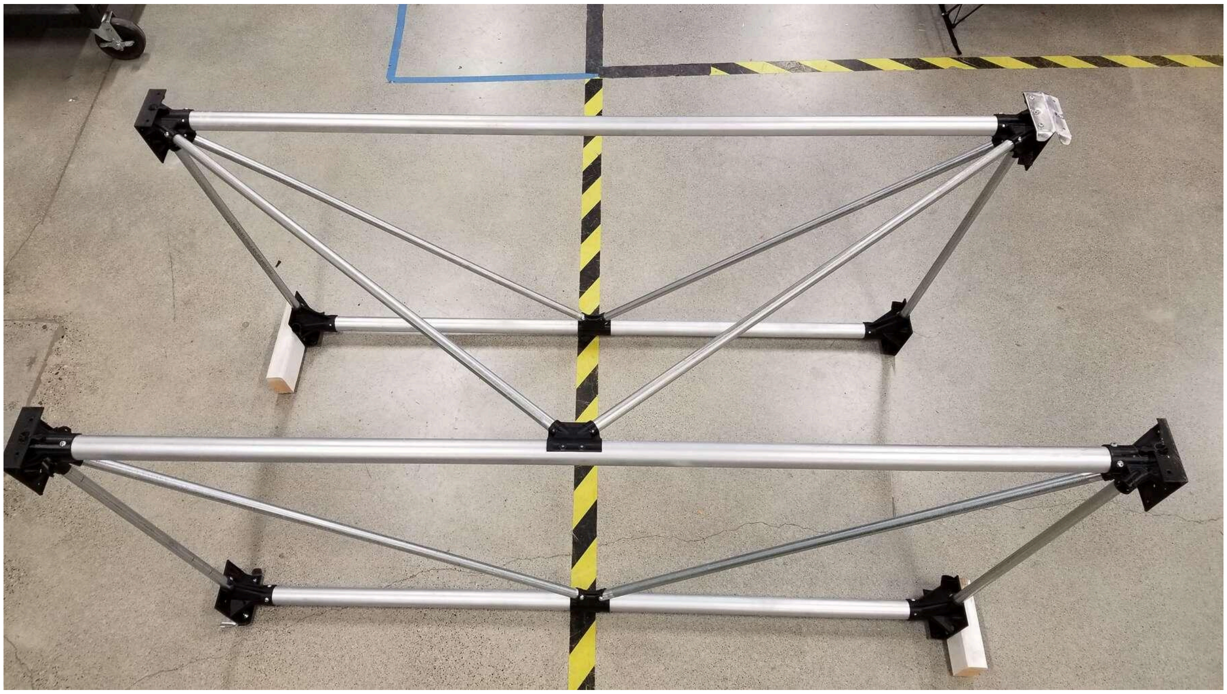
Upgraded plasma-cut endplate truss included an aligning feature, and locking pins.



Latest **hybrid truss** design using small 3D printed capture funnels for easy robotic alignment, while retaining the strength of metal-to-metal contact along the endplates. This iteration also includes basalt fiber diagonal tension rods, and a small spring-loaded capture pin for full push-connect operation.

Hybrid truss endcaps, which wrap around 1x1 inch steel rectangular tubing to self-align during docking. These are 3D printed from carbon fiber reinforced polycarbonate (PC-CF), and retained to the truss via stainless M3 screws (and possible future adhesive).

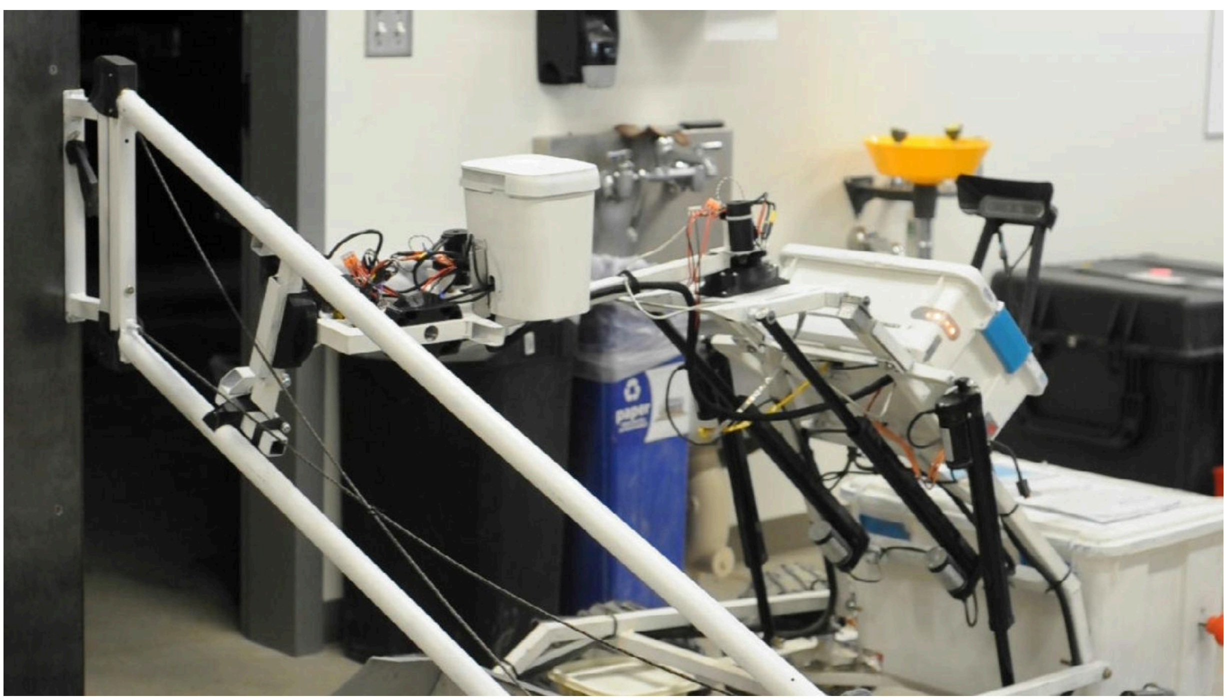
Truss compressive forces are steel-to-steel, and these seem robust to docking forces, but will break on large bending or tensile loads, so might be better as stamped metal.



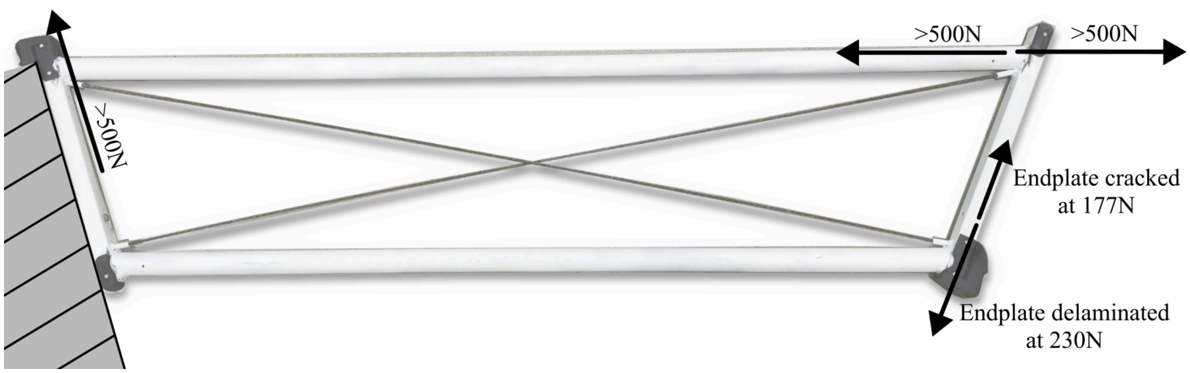
Full size L-truss module prototype built from steel tubes and plastic joints. These were useful for understanding the geometry and forces during truss-to-truss connection, and understanding the end connections, but the plastic joints were the limiting factor during load testing. These failed at less than 100 kgf on a two-segment arch.

Welded tube truss, gripped by prototype robot end effector, which levers the rotating left gripper outward to grip the parallel truss tubes.

Plasma-cut endplate flat L-truss, demonstrating docking attempts (unsuccessful) with robot arm.



Hybrid truss, during successful teleoperated robotic assembly and disassembly demonstrations.



Results of five load tests on hybrid truss docked to wall plate (as above), in Newtons of force. Pure tension, compression, or cross translation all sustained over 500N of load (the limit of our hand force gauge). Bending loads cracked the wall endplate at 177N, and broke it at 230N.

Final full-size L-truss parameters:

- Base angle: 22.5° for our prototype L-Truss endplates, which makes each truss 45 degrees from the next. A smaller angle requires more segments per turn, but has a smoother overall look to curves.
- Segment length: 1.5 meters (5 feet) on the long edge. This is constrained by transport logistics, and the robot's end effector torque capacity.
- Main tubes: 35mm diameter hollow high strength low alloy steel tubes.
- Endplate tubes: 25x25x1.6mm rectangular hollow steel tubes, welded with MIG or TIG to the main tubes.
- Mass: 3kg per module when fabricated in welded steel in flat 2D version.
- Connections: spring loaded pin connection, see Appendix A.3.

For demonstration in 1/10 scale, we have a 3D printed PLA plastic model with 3.5mm diameter main truss tubes.

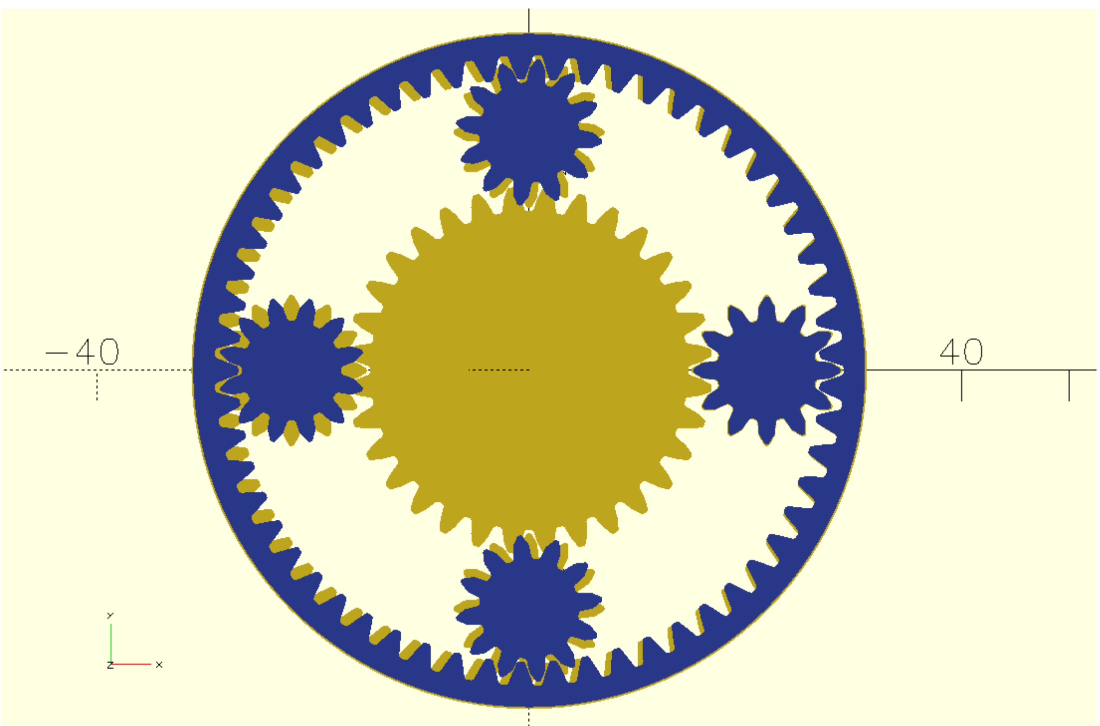
4.2 Robot & End-Effector

Our primary robot platform is the **Excahauler**, which excavates and hauls material, and was built for the 2022 NASA Break The Ice lunar permafrost mining challenge. It is designed to complete a variety of construction tasks, and had a large coarse front arm consisting of an excavator-inspired boom and stick joints, but did not have the 6DOF dexterity required to assemble modules.

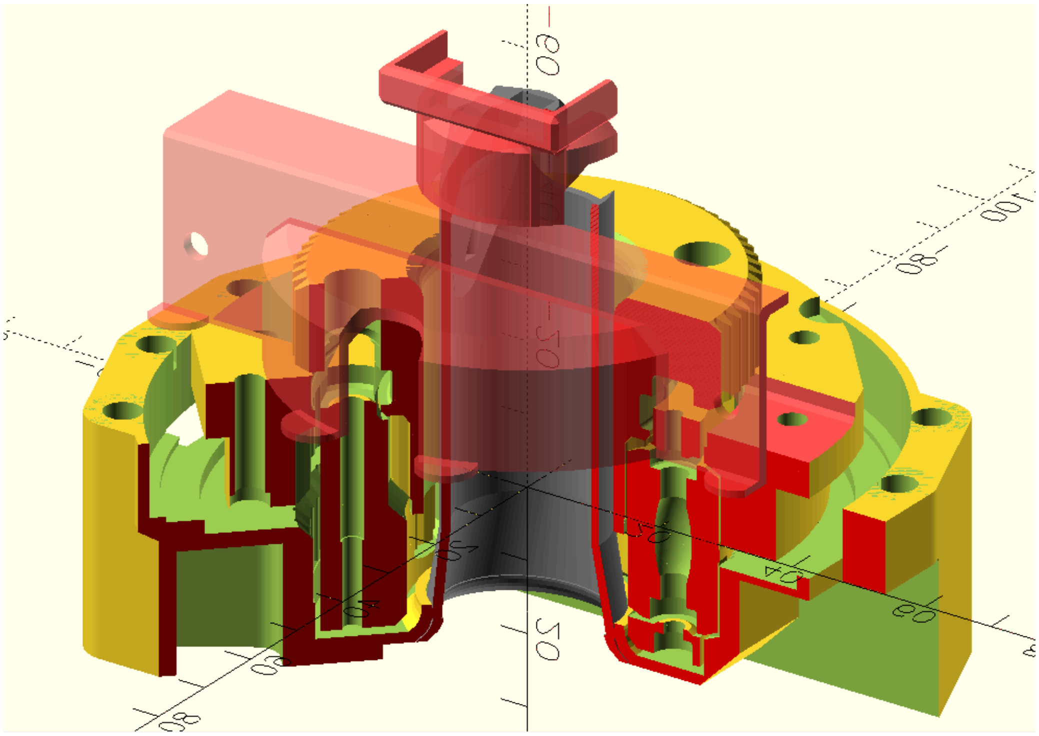
4.2.1 Robot Arm Actuator

We developed our own **custom arm actuators** using a stepped planetary (Wolfrom) gear reducer system, which we 3D printed from polycarbonate plastic and off-the-shelf sealed bearings. The 1x1 inch arm frame steel parts slot into spaces in the 3D printed gears, and the main bearings bolt directly through the printed parts into the steel frames. Stepped planetary gives high single-stage gear reduction similar to strain wave, in our case 2500:1 reduction from motor to output, so that we still have enough torque to lift several kilograms at the end of a 0.5 meter arm. 3D printing the geartrain is not good for strength or precision, but lets us customize our own parts (the gearbox on the robot is our 6th major revision of the design) and quickly manufacture our own upgraded repair parts, including at a remote test site or on a future planetary surface. Virtual spare parts could be sent from Earth, or customized in situ.

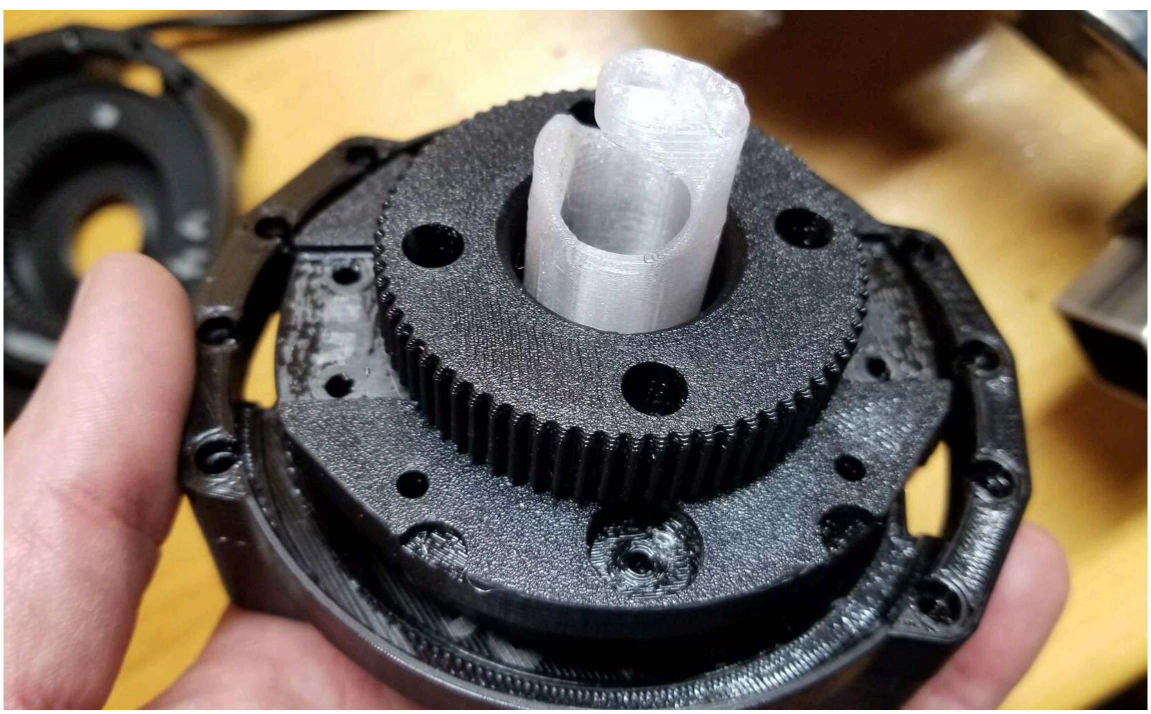
Power is provided via a 24VDC motor bus, driving an inrunner brushless motor (Skyquist BL3670, 1900KV) via an off-the-shelf speed controller (open source BLHeli_S based J-H-30 type Cyclone 45A). Control is provided by an onboard microcontroller (Arduino Nano 328P) using a magnetic angle encoder (AS5600 sensor over I2C, 4096 counts per arm rotation) and talking to the rest of the robot over the USB bus. In principle this actuator should be capable of hard vacuum operation with some minor material upgrades.



Our stepped planetary has the motor indirectly drive the sun gear (yellow, center), which spins the input planets (yellow behind blue planets) relative to a fixed ring gear (yellow behind blue ring gear). Each revolution of the planets advances the output ring (blue ring) by one tooth.

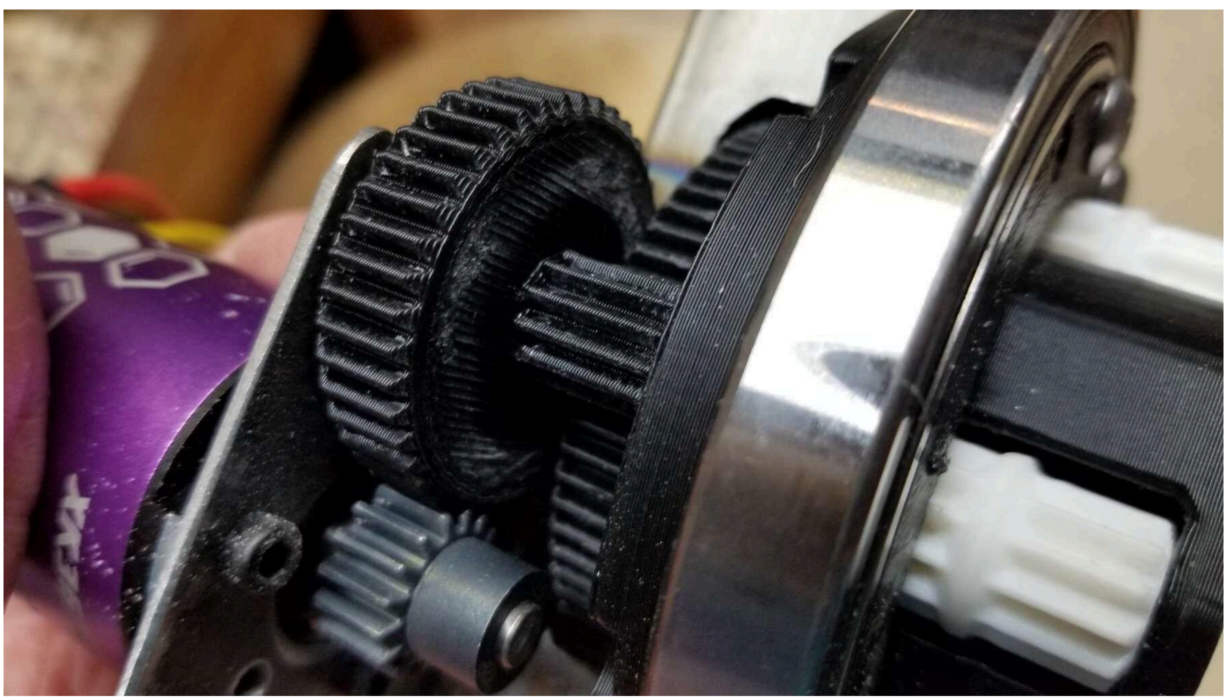


3D cutaway showing the sun input gear (top), fixed encoder magnet holder tube (center), planet carrier and one planet gear in cutaway, and the two ring gears wrapped around the planets. It has been a challenge to manage clearance between the many moving parts.



Arm reducer gearbox, without bearings or steel frame parts.

Open gearbox showing the output ring gear and planet carrier, which is numbered for the corresponding planets (which are each individually timed to the ring gears).



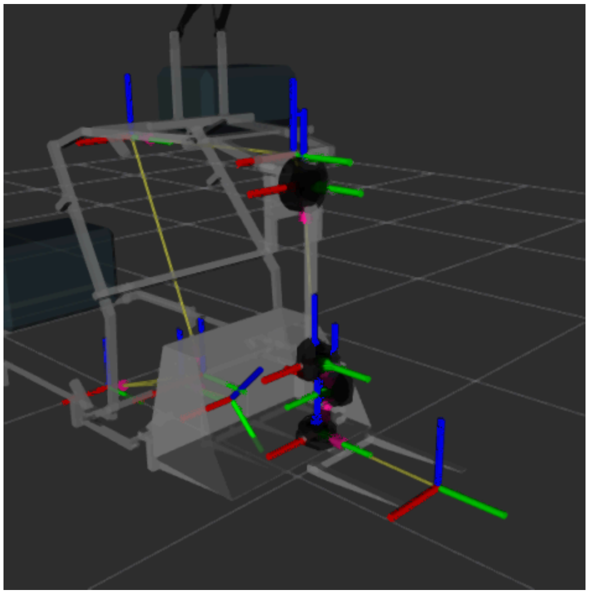
The brushless motor spins an intermediate reducer gear, which spins the sun gear, which drives the planets, which moves the arm.

The arm's steel parts have gaps for the gears, encoder magnet, and a plate for the motor. The encoder board mounts onto the M3 holes here. We plan to add better wiring protection once the wiring has stabilized.

The gearboxes are identical for 3 of the 4 arm joints, with the first drive gearbox having an extra printed-in flange to mount to the robot's tool coupler.

Overall, the arm gearbox has been useful, but required substantial development:

- Early gearbox designs without a planet carrier would not transmit the expected torque, due to the planets tilting under load and losing energy to tooth friction. Our final planet carrier includes a full set of bearings, allowing good torque amplification.
- The initial all-plastic printed planet carrier split in half under the expected torque, requiring steel bolts to be added for reinforcing.
- An hour-long wear test revealed the planet carrier and sun would move vertically, causing friction and wear, requiring the addition of bearings to constrain their vertical motion.
- Debris tolerance of the geartrain could be improved, any debris ingestion results in alarming sounds and compounding tooth damage during operation.
- An earlier hobby grade speed controller would move the motors only in a jerky fashion, and not symmetrically in forward and reverse. BLHeli_S seems more tuneable.
- Motor startup current is high, exceeding 10 amps, and will brown out the motor controllers without an onboard voltage source such as a 6S lipo battery.



The final robot arm consists of these joints:

1. Boom linear actuator to frame
2. Stick linear actuator to boom
3. Tilt linear actuator to stick
4. Arm0 gearbox to long arm frame
5. Arm1 gearbox to shortest arm frame
6. Arm2 gearbox to short arm frame
7. Arm3 gearbox to truss coupler
8. Truss coupler linear actuator grabber
9. L-truss module on grabber

The long kinematic chain results in a large working volume up to several meters high and about a meter from the robot, but the gearboxes have about one degree of backlash, so we need good self-aligning geometry to successfully assemble trusses. The encoders do see this backlash, so in theory could compensate for it.

4.3 Software

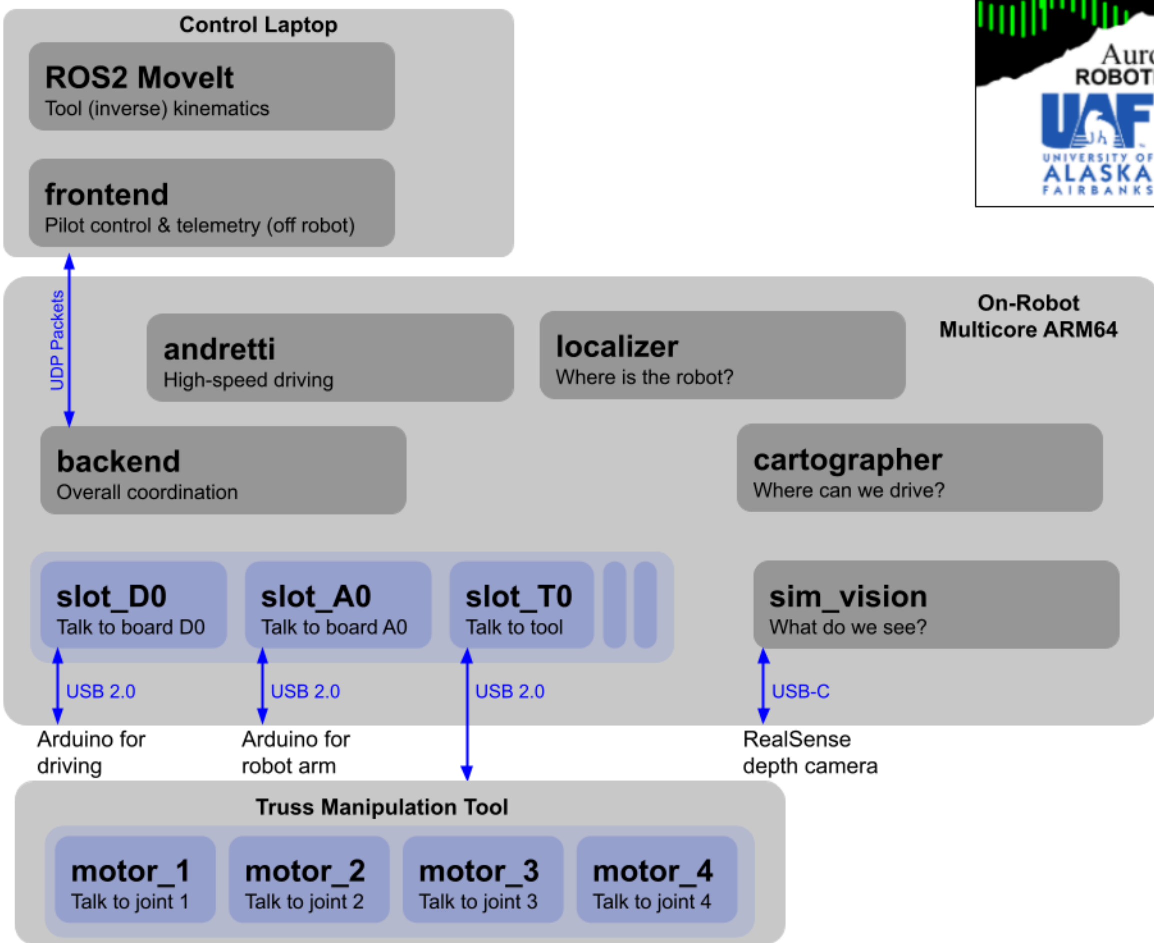
Our simulation stack is based on the Godot game engine and our custom terrain simulation:
https://github.com/AuroraRoboticsLab/GodotRobot

Our control stack is the Aurora Robotics Lab autonomy stack, available here:
https://github.com/AuroraRoboticsLab/MiningRobot

It is built in C++, and has been built up since 2013 by a variety of students for robotic tasks. Main features include:

- Lightweight compiled C++ to run efficiently on onboard ARM CPU.
- Support for teleoperation or limited autonomous operations, including computer vision marker based localization and obstacle avoidance path planning via A*.
- UDP communication for reliable operation over lossy networks.
- Timeouts and automated reconnection.
- USB device hotplug support via the 'nanoslot' architecture.
- Support for angle encoders including multiple IMUs.

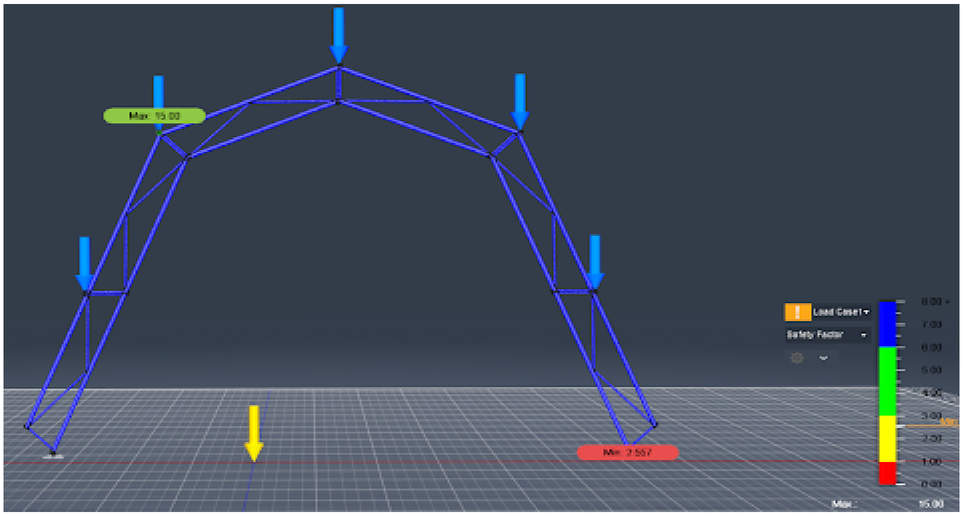
Existing Excahauler Software Stack:
Logically UNcoupled Architecture Technology for Intra-robot Communication - **LUNATIC**
Extended to include tool architecture.



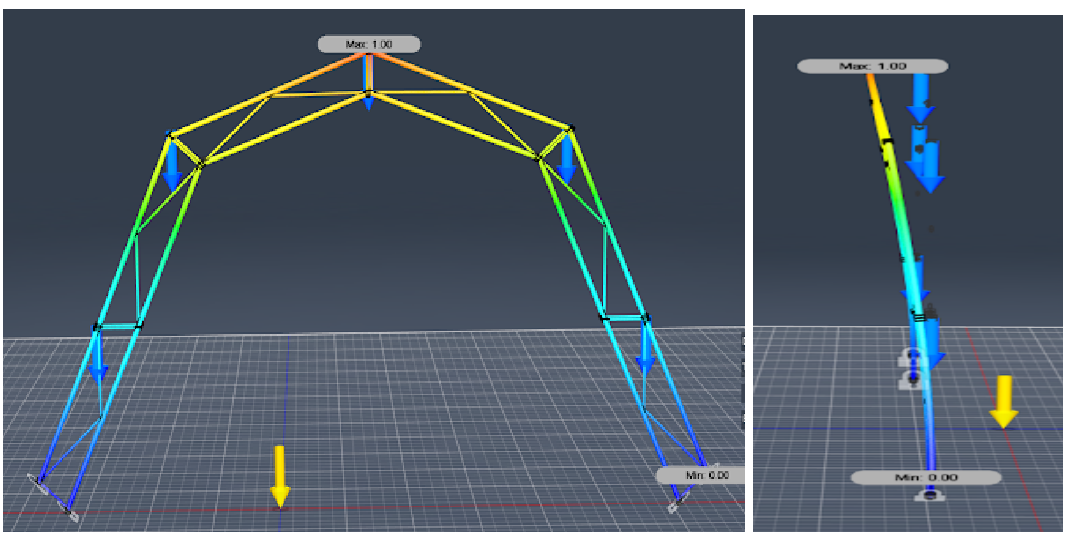
We have worked to take advantage of ROS2 features such as MoveIt path planning, and have built a URDF file for the excahauler robot and the arm we built. We have not completed the actuator control integration for moving the arm under MoveIt control, but this would be more predictable than teleoperation for repeated assembly.

5. Testing and Validation

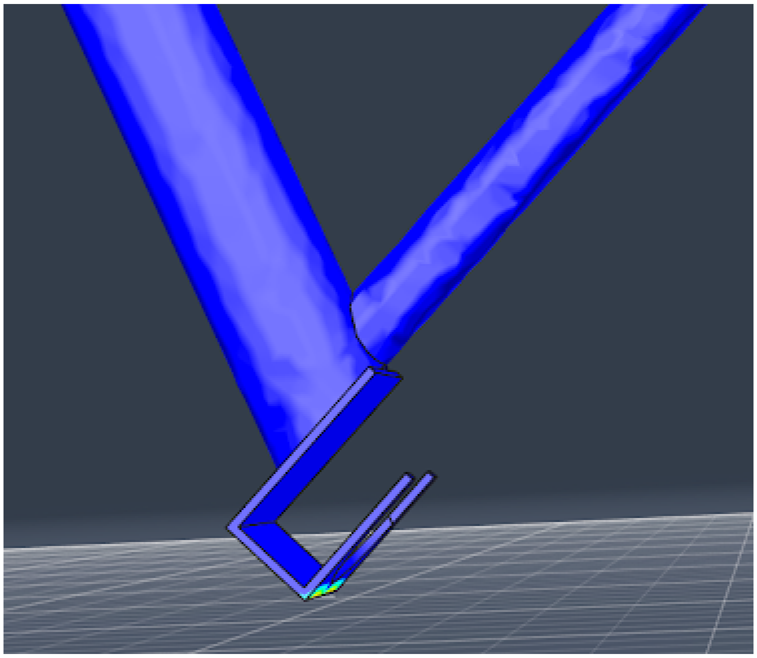
Finite Element Analysis: Performed for trusses and components in Fusion360.



With a 500N compressive load, as would be expected when loading the structure with lunar regolith, FEM revealed a minimum safety factor of 2.6, and maximum of 15.0.



Under 500 N axial load, the structure exhibited a critical buckling load 14.3 times higher than the applied load, indicating a strong safety margin and good resistance to out-of-plane deformation under compressive stress. This does assume the foundation is securely restraining horizontal motion (plausible given a well-compacted foundation) as well as rotation (only plausible for a multiple element structure, where the elements restrain each other via their uprights).



FEM of the anchored truss segment under load revealed reaction forces of -98.4 N in the x-direction, 379.9 N in the y-direction (vertical), and negligible force in the z-direction, resulting in a total reaction force of approximately 392.4 N. The expected lateral force requirement for stability was estimated at 160 kgf; however, the simulation showed only ~20 kgf was needed, yielding an effective safety factor of 8.

Load Testing: We built a 1/10 scale model from PLA and tested in local basalt dust. Anchoring the ends, as predicted, dominates the arch performance.

	Earth Gravity	Lunar Gravity	Mars Gravity	Mars Gravity, 10x scale
Load Tested	12kg	72kg	36kg	36 tonnes

Performance: Trusses passed dust-loading tests and surpassed design expectations for strength. Stability seems to improve for larger structures, other than in twisting modes.

Challenges: No full-scale demonstration, delays in full-scale testing and MoveIt integration.

6. Challenges and Mitigations

Over the course of the 2024–2025 academic year, our team encountered a range of technical, organizational, and scheduling challenges. While some were anticipated, others emerged unexpectedly and required adaptation in both planning and execution. This section outlines issues that impacted project progress and the strategies we used, or would recommend, for addressing them.

6.1 Design for Manufacturing Delays

One of the most significant technical challenges we faced was the late development of an efficient method for fabricating full-scale steel truss segments. Initially, our designs did not account for production scalability or material handling limitations in our machine shop. By the time we transitioned to using a CNC plasma cutter to speed up the process, much of the semester had passed, and critical manufacturing time was lost.

Mitigation: Future efforts should prioritize design-for-manufacturing (DFM) planning. A focused design sprint to validate fabrication approaches as early as possible would help to prevent similar delays.

6.2 Tolerance and Precision Issues

During end-effector testing, we discovered that the planetary gearboxes in our robot's manipulator arm introduced significant backlash, resulting in ±2 inches of positional uncertainty in all directions at the tool tip. This presented a major barrier when attempting precision alignment.

Mitigation: To reduce positioning uncertainty, future hardware iterations should incorporate either closed-loop control with real-time feedback or lower-backlash gear solutions. Mechanically, further self-aligning connection features on the truss would also further reduce the burden on precision manipulation.

6.3 Incomplete MoveIt Integration

Although we developed a working inverse kinematics model of the Excahauler arm using ROS2 MoveIt, we did not have time to integrate this functionality into our main control stack (LUNATIC). As a result, all robotic testing was conducted via manual teleoperation, and assisted path planning was not available.

Mitigation: To avoid bottlenecks during final integration, early semester goals should include a functional test of software subsystems, potentially on scaled-down hardware analog. Integration should not be deferred until after hardware is complete.

6.4 Team Availability and Scope Overreach

Many team members became largely unavailable due to other duties, which significantly impacted our ability to meet scheduled deliverables. Without sufficient capacity, we were forced to down-scope from a full-scale arch demo to a partial robotic test and scale model.

Mitigation: In retrospect, our original project scope exceeded what was feasible for a small team with other responsibilities. We now recognize the need to plan conservatively and account for potential attrition. Defining a minimally viable demonstration earlier in the semester would have ensured a higher completion rate.

6.5 Environmental Constraints

Scale backfill testing using regolith simulant was successful but was not performed at full scale due to seasonal and schedule limitations; snow was no longer available as it melted, and we ran out of time to complete the full arch structure.

Mitigation: For future seasonal testing, snow-related demonstrations should be scheduled early in the spring semester with strict deadlines or coordinated with cold storage resources where feasible.

6.6 Communication and Project Management

Initially, the team operated without a clear leadership structure, relying on informal task division and assumed accountability. This led to miscommunications, missed deadlines, and a lack of clarity about task ownership.

Mitigation: Midway through the project, a leadership role was established to coordinate scheduling and ensure follow-through. We now understand that leadership and project structure are necessary even in small teams.

These challenges, while limiting our ability to meet all original goals, provided valuable learning experiences. The lessons we drew from them shaped not only the final deliverables of this project but also our readiness for future multidisciplinary engineering efforts.

7. Lessons Learned

Participating in the 2024–2025 X-Hab Challenge provided our team with significant technical and organizational insight. Although we did not achieve all of our original goals, the experience yielded invaluable lessons across engineering design, project execution, and team dynamics.

7.1 Systems Engineering

This project marked the team’s first real exposure to formal systems engineering. Concepts such as requirements flowdown, organized risk management, interface definition, and trade studies were new to us at the beginning of the academic year. Over the course of the project, we came to understand the importance of clearly defining success metrics and validating designs against those criteria. In-depth documentation and planning can help keep complex interdisciplinary efforts grounded and coherent.

7.2 Leadership and Team Structure

At the outset, we believed our small team could operate without formal leadership, and assumed that collaboration and individual initiative would be sufficient. However, as the semester progressed and deadlines approached, it became clear that a lack of defined leadership led to missed deliverables and uneven task distribution. In response, we established a more structured leadership approach, with Andrew taking on scheduling, delegation, and status tracking. This shift was critical in helping us recover momentum and complete deliverables.

Lesson: Even smaller groups need clear structure and plenty of communication. Defined leadership in projects like this is necessary.

7.3 Planning and Scope Management

A key takeaway from this project is the importance of conservative planning. We initially overestimated what we could accomplish given our team size, other academic obligations, and tool learning curves. For example, our fabrication process for full-scale trusses was not optimized until the semester was nearly over, which derailed our full-scale demo plans. Similarly, software tasks such as integrating MoveIt into the robot's control stack proved more complex and time-consuming than expected.

Lesson: Promise less than we think we can deliver. Under-promising gives room for flexibility and results in better outcomes. Plus, we will likely end up over-delivering, which is great for morale.

7.4 Technical and Fabrication Lessons

Team members gained firsthand experience with the challenges of designing for manufacturing. Unlike previous class projects that prioritized one-off prototypes, this effort required repeatable, scalable components. Fabrication tolerances, especially in our robotic end-effector and truss interfaces, emerged as a recurring issue, driving home the need to account for real-world imperfections in both materials and assembly processes.

7.5 Interdisciplinary Collaboration

Working across mechanical engineering, computer science, and computer engineering introduced challenges in aligning terminology, toolchains, and workflows. However, this diversity of expertise also led to more robust design choices and fostered a broader understanding of how software, hardware, and structural design must interoperate in real systems.

8. Educational Value

This project offered substantial educational benefit across technical, organizational, and outreach domains. Through participation in the X-Hab Challenge, we gained real-world experience in interdisciplinary engineering projects, collaboration with NASA personnel, and iterative problem solving under tight constraints.

8.1 Technical and Design Experience

All team members engaged in hands-on engineering work across multiple domains, including:

- **CAD and Simulation**: Designing truss geometries and connection mechanisms using Fusion360 and performing structural analysis through finite element methods.
- **Fabrication and Prototyping**: Gaining experience with plasma cutting, TIG welding, and 3D printing to build scalable structural components.

- **Robotics and Control**: Developing a modular robotic arm with custom actuators, integrating ROS2 and MoveIt software stacks, and executing teleoperated truss manipulation.
- **System Integration**: Learning to manage hardware-software interfacing, actuator tuning, encoder feedback, and robot kinematics.

Students encountered realistic engineering trade-offs related to weight, tolerance, material properties, and manufacturing constraints.

8.2 Systems Engineering Process

This was the team's first full exposure to a structured systems engineering lifecycle, including:

- Requirements development and flowdown
- Trade study evaluations and baseline selection
- Interface definition and risk mitigation planning
- Design reviews with NASA engineers (SDR, PDR, CDR, PCR)

We are all much more confident in organizing complex projects, evaluating design decisions, and navigating the documentation and communication standards expected in systems engineering environments.

8.3 Interdisciplinary Collaboration

The project spanned multiple engineering disciplines, including mechanical, computer, civil, and electrical, as well as computer science. Students learned to communicate across fields, coordinate parallel tasks, and align their design efforts with shared milestones. Weekly meetings and peer reviews kept both physical and software systems in sync and prepared us for collaborative careers in multidisciplinary teams.

8.4 Outreach and Communication

Throughout the year, the team engaged in multiple outreach activities, sharing the project with a broader audience:

- **Engineering Open House**: Live demonstrations and conversations with the public and prospective engineering students.
- **FTC Robotics Tour**: A guided tour and technical presentation for a local FIRST Tech Challenge team.
- **Party in the Park**: Informal community outreach and signup event to build public awareness and inspire local student interest in lunar exploration and robotics with live robot demonstrations.

Videos of our robots are available at AuroraRoboticsLab.com

8.5 Academic Impact

The project was conducted within the framework of CS 493 (special topics for fall semester, due to course approval deadlines) and CS 454 (systems design seminar for the spring semester, now approved as a regular course) at the University of Alaska Fairbanks. These courses introduced structured design methodologies and provided academic credit for student contributions. The robotics and structural engineering work directly contributed to students' professional development and future research pursuits.

9. Future Work

We would like to continue to apply the modular robotic construction technology that this project developed. This year's work laid a strong foundation, but several advancements remain as future work:

- **Full-Scale Robotic Assembly**: A priority is to complete the full-scale arch using robotic control to demonstrate reliable connection and lift sequences. This includes a revisit of site preparation, structural assembly, and regolith simulant backfill using robotic tools.
- **Improved MoveIt Integration**: While the robot's inverse kinematics are modeled in MoveIt, deeper integration with our control stack is needed to enable sense-plan-execute motion planning with collision avoidance, and semi-autonomous alignment tasks.
- **Tolerance and Manufacturing Optimization**: Future efforts should focus on reducing end-effector backlash, tightening mechanical tolerances, and refining the steel truss manufacturing process for repeatability and scalability.

These next steps will move the system closer to a fully functional lunar prototype and provide a robust platform for future student research and NASA collaboration.

9.1 Acknowledgements

Aurora Robotics Lab received excellent support this year from our NASA subject matter experts. In particular, we received extensive recurring help from:

- Matthew Mahlin
- Greenfield Trinh
- John Cooper

Many other NASA personnel attended our reviews and gave us useful feedback.

New students Allison Bergt and Artyom Kesler helped refine our prototypes, and Brandon Kallenback helped pick our new arm angle sensor and optimize our electronics.

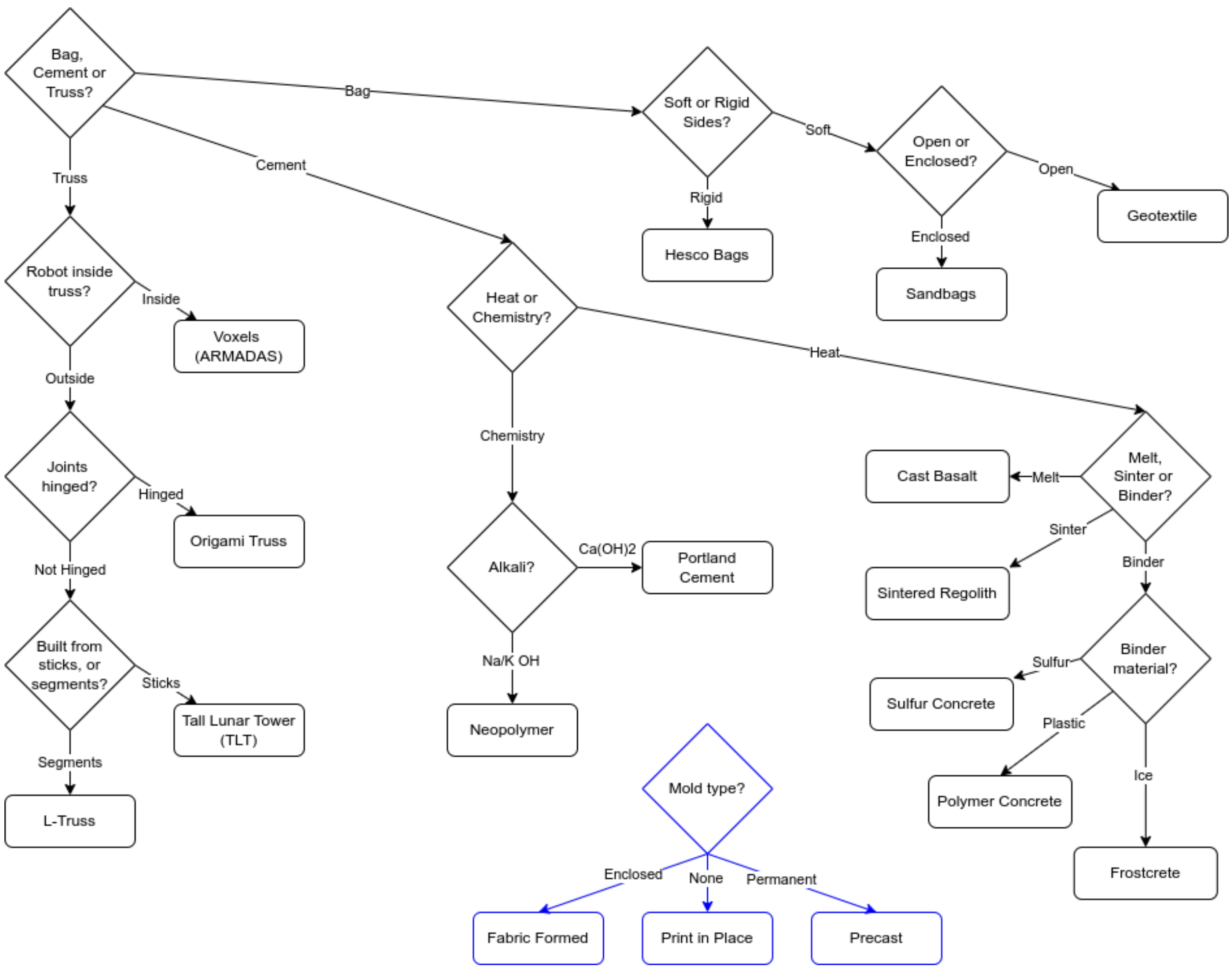
Over the years our lab has received prize money from the NASA Break The Ice challenge, and funding from the Alaska Space Grant, National Space Grant, National Science Foundation, and several private donors.

Our robot control software stack and hardware design language is the result of the work of dozens of UAF students over the past 12 years.

10. Appendices

Appendix A.1: Summary of Construction Trade Space

The trade space for extraterrestrial construction is extremely large:



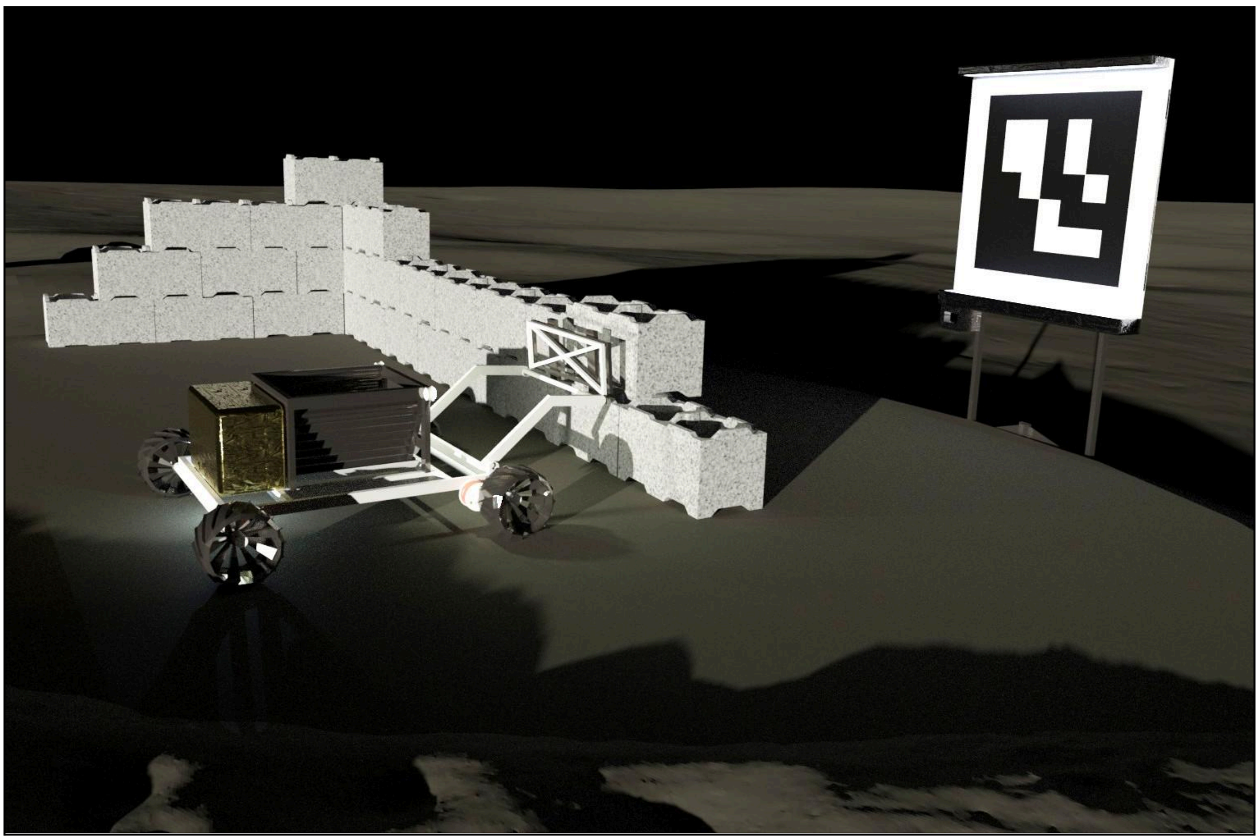
Above, a selection of possible extraterrestrial modular construction approaches.

Appendix A.2: Alternate module designs explored

During the fall semester prior to our critical design review (CDR), we explored many possible construction modules, in addition to the L-truss that we eventually tested.

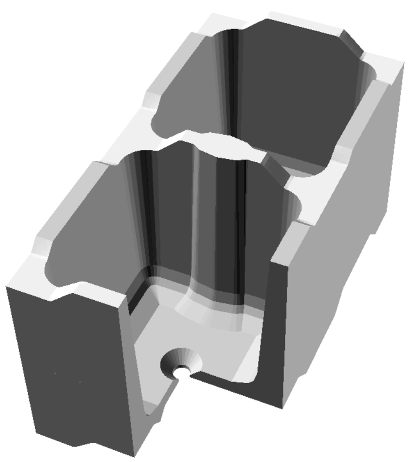
Interlocking Cinderblocks

Our original proposal prior to meeting with our NASA subject matter experts was a regolith-derived concrete to make a cinderblock like shape:



An autonomous construction robot dry-stacks construction modules made mostly from lunar highlands regolith to build a retaining wall around a lunar landing pad. (Render from our X-Hab proposal.)

1/10 scale dry-stacked modular wall, assembled manually in fine basalt dust. Basalt fiber rods could act as continuous vertical rebar, and basalt fiber strands could tie the rebar back into the dust like a geotextile anchor (examples of both on left).



Cutaway of a potential construction module: a 200 x 200 x 400 mm self-aligning cinderblock formed from regolith.

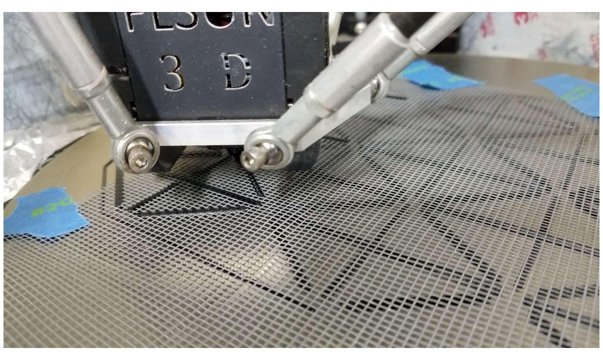
Full scale teleoperated test of our multipurpose robot stacking cinderblocks (17kg) with forklift-style forks.

Geopolymer concrete tiles cast from >98% LSP-2 lunar highlands regolith simulant, using an interlocking tile mold of our design. The slabs on the right were vitrified and welded (!) with concentrated solar. Prepared by our collaborator Lucas Samuel in Belgium.

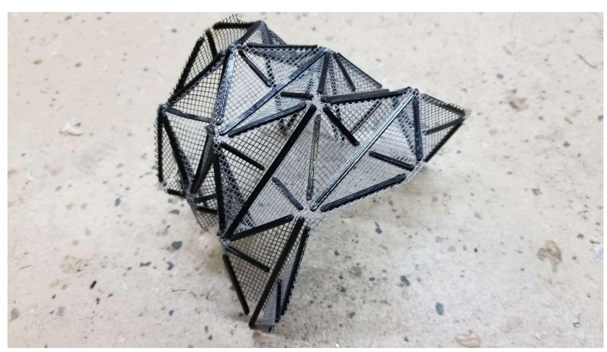
Origami Truss Deployment

As a way to simplify deployment, an origami-type design could be very simple, potentially as simple as pulling open a flat structure to produce a 3D object.

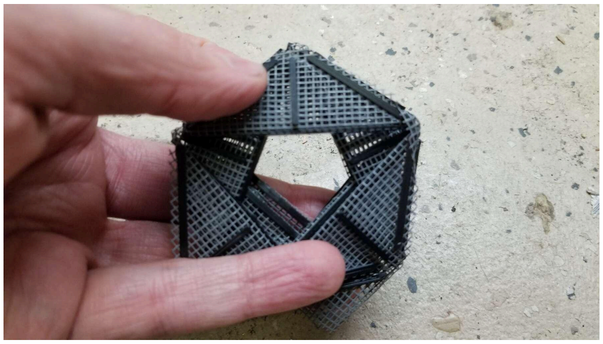
We explored several variants of the diamond buckling pattern (Yoshimura).



Print-in-place diamond buckling pattern on flexible window screen.



Origami mesh deployed in 3D.



Folded up origami mesh (print in place).

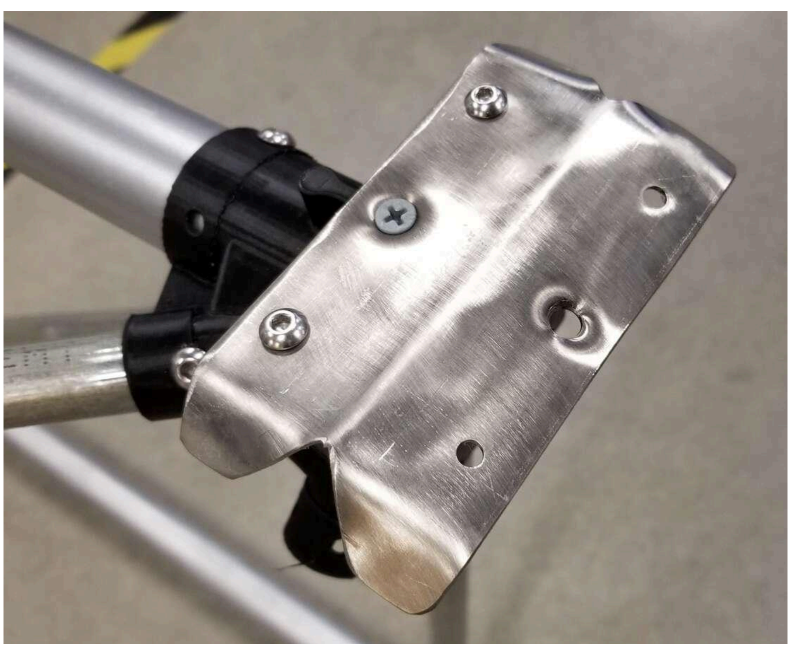
Scaled up origami design, composite rods with defined motion along 3D printed joints.

Origami packaging with discrete rigid truss segments. To support a heavy regolith cover, the tubes and connections need to be thick, which complicates origami-style deployment.

During scale-up tests, we found truss designs got stronger due to trusses supporting each other, and origami designs got weaker due to buckling along unplanned modes.

Appendix A.3: Latching Mechanisms Explored

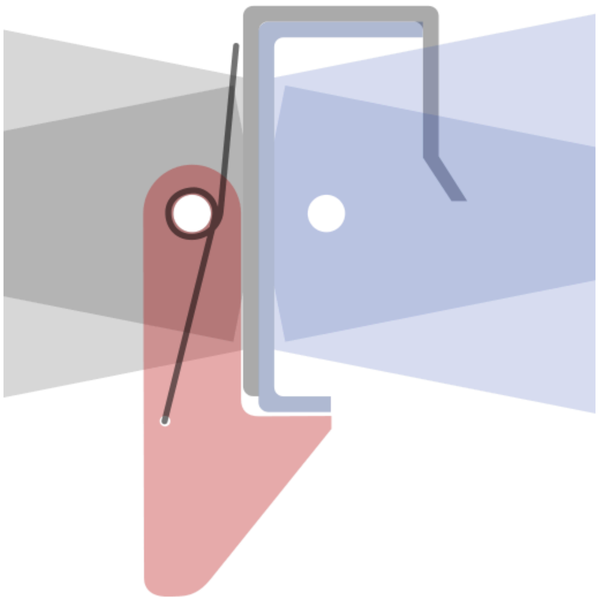
Construction modules need to connect together using some mechanism. Our early tests indicated screws would be very challenging for robots to assemble, so we looked at latch or spring-loaded pins for a tool free push connection approach.



This screw-connect plate uses formed conical funnels to self-align adjacent trusses, and make feeding a screw easier.

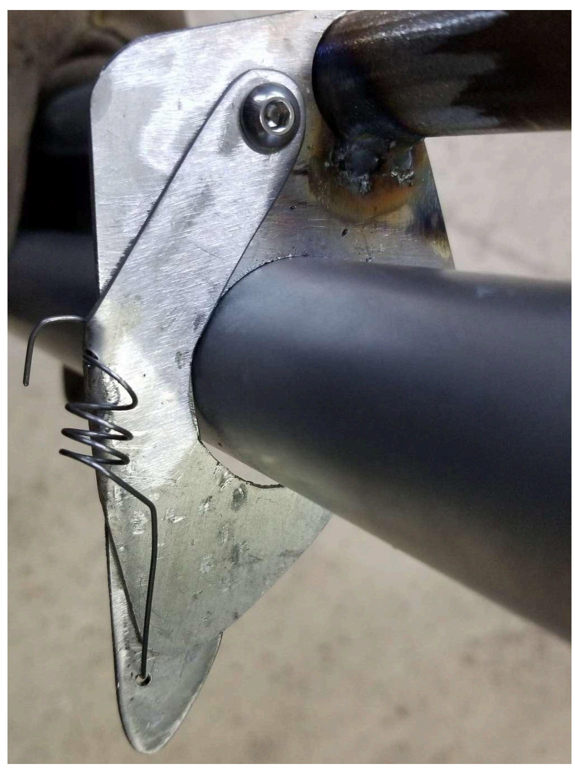
Robotic handling of screws seemed very challenging, requiring precise alignment and surprisingly large forces in our development tests.

We switched to push-connect approaches to simplify the robot's task.



Push-connect latch CAD: the moving endplate (blue) slides up into place, and the latch keeps it from sliding back out.

Welded steel prototype, which worked well, though it required quite a lot of hand welding.



The above latch is used to connect one truss's upright (small tube) to the next truss's main tube (large tube). This could work with most endplate latches to provide multiple points of contact between adjacent trusses, holding them securely.

This spring-loaded pin sits inside a hollow square tube, with a square spring-loaded nut pushing the pin out.

This pin falls into a simple chamfered hole on the other truss element, and can be removed by pulling the pin, allowing the elements to slide apart.

This approach is used on the hybrid truss for push-connect capture.

If arch segments get slightly longer at each segment, all the segments on one side of an arch can fold up in a nested fashion. This could allow half the truss-to-truss connections to be made before deployment, though it comes at some cost in packing efficiency and structure generality.

Nested arches could be deployed very rapidly by pulling a cable wound through the stack, closing up each end joint one by one, and unrolling an entire half-arch. This could then be connected to the mirror half-arch, stood up, and connected to the structure.